Fermi National Accelerator Laboratory

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Model for CMS Jet Resolution

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Introduction:

The CMS collaboration has chosen PbWO4 crystals for their electromagnetic (EM) calorimetry (ECAL). This choice was made to provide CMS with the best possible EM calorimetry. However, the choice of hadron (HAD) calorimetry (HCAL) is more conventional; copper absorber sampled by scintillator. This arrangement is clearly rather highly non-compensating. Therefore, there are potentially issues of severely poorly measured hadrons and jets due to fluctuations in the development of hadronic showers in the ECAL and HCAL compartments of the calorimeter system. [1] The purpose of this note is to make a first pass at these issues using test beam data taken by the US CMS HCAL group. [2]

H4 Test Beam Results:

Data was taken in the CERN H4 test beam with incident pions, electrons and muons. The calorimeter array consisted of a faithful representation of the proposed CMS "baseline" calorimetry. [3] The ECAL compartment was calibrated using electron beams and was found to be a linear device capable of precision measurement of EM energy.

The HCAL compartment was calibrated using muons and was exposed to beams of pions of 15, 35, 50, 80, 120 and 375 GeV energy. During these exposures the ECAL was placed in front of the HCAL compartment. Gaussian fits were made to the histogrammed data at each energy. The resulting mean energy with respect to that for electrons in ECAL is shown in Fig. 1. There is evidence that e/h is much different from 1. For single hadrons one can alleviate that effect by using a relative calibration of ECAL and HCAL which differs from that obtained using muons. For example, E = alf*ECAL + HCAL. Data are shown in Fig.l.a and Fig.l.b for alf = 1.4 and 1.0 respectively. The lines shown in Fig.l are of the form:

$$pie/e = a + b*\ln(E) \qquad (1)$$

For alf = 1.4, a = 0.779 and b = 0.0425 while for alf = 1 we find a = 0.64 and b = 0.055. At a fixed energy, say 120 GeV, for alf = 1.4 one has pie/e of 0.98, while for alf = 1.0 one finds pie/e = 0.90. In both cases there is a 15% variation in pie/e as a function of energy from 15 to 375 GeV.

Note that in a jet, with its high local parade density, one is likely to be unable to sort out which energy deposits are neutral and which are due to charged hadrons. Thus one cannot correct the hadronic energy by the pie/e ratio in a particle by particle energy dependent fashion. One can only pick a single calibration constant. In what follows alf = 1 is defined, although that may not be the optimal choice of relative ECAL:HCAL calibration.

The single electron energy resolution is very good and is assumed to be perfect in what follows. The single hadron energy resolution is taken from the test beam data as summarized in Fig.2. The resolution depends on the relative calibration alf, as might be expected in a highly non-compensating device. Shown in Fig.2.a is dE/E for alf = 1.4 and in Fig.2.b one plots dE/E for alf = 1.0 for 15, 35, 50, 80, 120 and 375 GeV. The plot axes are 1/E and (dE/E)^2 because, for a calorimeter characterized by a stochastic and a constant term in the energy resolution, the data should appear linear using those variables as axes. Indeed, we observe roughly linear behavior.

$$(dE/E)^2 = (a^2)/E + (b^2) \qquad (2)$$

For alf = 1.4 we find a = 1.01 (GeV units) and b = 0.063, while for alf = 1.0 the resolution is worse, a = 1.2 and b = 0.08. Note that these resolutions are worse than what one observes for pions interacting only in HCAL and what one observes in similar HCAL structures. [4] The agreement with homogeneous Fe/scintillator structures was checked using data for events where the pion did not interact in ECAL. We adopt the resolutions resulting from the choice alf = 1.0, as they appear to be a "worst case scenario".

<u>Simple Jet Fragmentation Model:</u>

Jets were modeled in a simple way in order to maintain the transparency of the relationship between single particles and jets. The jet Pt was chosen and then the jet was fragmented into particles characterized by a momentum fraction z = p||/Pt, (z > mpie/Pt), a transverse momentum kt, and a charge q.

$$D(z) = z(l-z)^a \quad (3)$$

$$dN/dkt^2 = \exp(-b*kt)$$

The charge was randomly chosen to be +1, 0 and -1. There was no correlation among the fragments nor among the variables characterizing the fragments. Thus, we adopt the simplest model which preserves the gross behavior of jets and their fragmentation.

Hence, the jet is defined to be an ensemble of charged and neutral particles localized in space. The shape of D(z) implies that the jet Pt is made up of many soft particles. Since the pie/e ratio is rather far from 1 at low energies, one expects that there will be a poor pie/e ratio for jets. The effective pie/e and resolution for Pt = 50, 100, 200, 400, 800 and 1600 GeV jets is shown in Fig.3. The pie/e is represented by the form given in Eq. 1 with the parameters for jets, a = 0.42 and b = 0.07. Note that Ptrec/Ptgen, the ratio of reconstructed to generated Pt. is taken as the jet analog of the single particle pie/e. Note also that for neutral energy, the contribution to the jet Pt is taken with "pie/e" = 1. At Pt = 400 GeV, <Ptrec>/Ptgen is ~ 0.85. Therefore, some calibration procedure will be needed in order to avoid the induction of large missing Et in an event due to jet energy scale nonlinearity.

The jet energy resolution is shown in Fig.3.b. Again, as the jet is an ensemble of many soft particles, the resolution is not badly degraded with respect to the single particle results. In fact, using the parametrization given in Eq.2, one finds for jets a stochastic coefficient of a = 1.0 and a constant terrn of b = 0.03. These results are better than the single particle results quoted from Fig.2.b, mirroring the fact that the jet Pt is built up of the energy of many fragments. However, the problem of differential energy nonlinearity remains.

Jet Corrections:

One can only attempt global corrections to the jet using global properties. In the context of this simple model, one can explore the transverse energy flow within the jet fragments. The dependence of Ptrec/Ptgen on the cone size within which fragments are accepted with respect to the jet axis is shown in Fig.4. Clearly, ~ 1/2 of the energy of the jet is contained in a "core" with R < 0.025. However, the fluctuations on the core, as shown by the rms error bars in Fig.4, are large. The mean value of R for a fragment in the jet is, <R> = 0.5, while the maximum R value of a fragment averaged over many jets is <Rmax> = 1.5. However, the large R fragments are soft, so that a search cone of R = 0.5 captures almost all the energy. In the present model, <kt> = 1.3 GeV, and <z>= 0.04 for a Pt = 500 GeV jet. The "leading fragment", zmax, averaged over many jets has <zmax> = 0.24, or typically 1 particle takes off 1/4 of the jet energy, while the mean particle energy is only 1/25 of the jet energy.

Although it may be possible to make corrections to the "core" particles in the fragment, clearly the hadronic cascade within the calorimeter will smear out the transverse information badly. Typically, the hadronic shower of a single particle in the jet is spread over dR ~ 0.1. Within the scope of this exploratory note, we will ignore the possibility of using the transverse information available in the ECAL and HCAL towers. Rather we concentrate on the longitudinal information in the 2 compartments, ECAL and HCAL, summed over the full R = 0.8 cone radius in transverse coordinates.

A "data set" of 2000 jets with Ptgen = 500 GeV was created with calibration alf = 1. Single neutral pions were assumed to be measured exactly. In contrast charged pions were shifted in the mean by the pie/e curve shown in Fig.l.b and smeared about that mean as indicated in Fig.2.b. The resulting histogram of fragments within R < 0.8 is shown in Fig.5.a. The mean and rms of Ptrec/Ptgen is 0.89 and 0.058 respectively. No long, non-Gaussian tails appear to have been generated at the < 1 % level. Therefore, it appears that severe energy errors induced by noncompensation are absent. In fact, one can attempt to correct the mean, as shown in Fig.6. That Figure shows a scatterplot of Ptrec/Ptgen against zo, the neutral fraction of the jet. Clearly, there is a correlation which survives the energy smearing. Not surprisingly, a jet which is mostly neutral, zo ~ 1, has a correct <Ptrec/Ptgen> ~ 1. A jet with low neutral fraction will have a Ptrec which badly underestimates the parent jet Pt. Note that <zo> = 1/3, averaged over all jets - by construction. A simple correction factor was applied to the jet energy as a whole.

$$Ptrec * [l+ (l - zo) * 0.2] \qquad (4)$$

The corrected jet histogram is given in Fig.5.b. Clearly, the algorithm itself does not induce tails at the 1% level. The mean and rms of Ptrec'/Ptgen are 1.003 and 0.054 respectively. Thus we have restored the mean and slightly improved the rms error. However, the coefficient in Eq.4, taken as 0.2, will clearly also be energy dependent. Taking the average over jets in Eq.4, one expects that, 1 - Ptgen/<Ptrec> = (l-<zo>)*a = (2/3)*a. Looking at Fig.3.a, there is a 25% variation of <Ptrec>/Ptgen for jets ranging from 50 to 1600 GeV. Therefore, a is a function of Pt and one will need to calibrate the correction of the mean. As an example, one can use Z+J events with Z -->ee in order to balance the Pt of the Z against the jet Pt. [5] Thus, knowing Ptrec and zo one can find a(Ptrec) and correct the jet energy so as to restore the linearity of the calorimetry.

It is unfortunate that zo is not an experimental quantity. What is available is the ratio of the energies in the ECAL and HCAL compartments, defined to be EM/HAD. The EM partition has contributions from the neutral pions and from the charged hadrons which interact within the ECAL and deposit some neutral energy from the first generations of the cascade within the ECAL. These processes are very complex, so that we use the H4 data itself, on an event by event basis, to model the ECAL and HCAL energies of charged fragments and their fluctuations. One finds that, for 500 GeV jets, the mean neutral fraction <zo>, averaged over many jets is 0.35 with a rms of 0.17. The mean fraction of the jet energy in the ECAL section is <EM/(EM+HAD)> = 0.51, with a rms of 0.15. The ECAL fraction has a contribution of ~ 0.33 from neutral fragments and ~ 0.20 from charged pions which begin to cascade in the ECAL compartment. The correlation of zo vs EM/(EM+HAD) = fern is shown in Fig.7.a. Clearly, there is a reasonable correlation. When z0 = 0, fem is still ~ 0.2 due to charged pion energy deposits in ECAL.

The correlation between Ptrec/Ptgen and fem is shown in Fig.7.b. Clearly, there is a residual correlation between these 2 quantities. We use the behavior given in Fig.7.a to correct Ptrec on a jet-byjet basis using fern to estimate zo' and using zo' in Eq.4 instead of the unmeasured variable zo.

$$zo' = a + b * fem \tag{5}$$

In Eq.5, a reasonable representation of the data is, a = -0.225 and b = 1.125. One can then use zo' in place of zo in Eq.4 to correct Ptrec. For Ptrec/Ptgen we have a mean of 0.89 with a fractional rms of 5.6%. For the corrected Ptrec using zo' via fem and substituting into Eq.4, one obtains a mean of 1.0015 with a fractional rms of 5.8%. in this case, the smearing between fem and zo is such as to still allow us to correct the mean but not to improve the resolution.

<u>Conclusions</u>:

We have explored the effect of noncompensation in CMS calorimetry using test beam data taken in the CERN H4 test beam. The CMS calorimetry has a substantial hadronic nonlinearity and a degraded energy resolution due to the decision to choose the best possible EM resolution. Compensation and precision EM calorimetry are known to be incompatible requirements.

We have explored the implications for CMS jet energy measurements. The jet energy resolution due to the nonlinearity and resolution of the CMS calorimetry leads to a 100% stochastic coefficient. The linearity can be recovered by correcting each jet individually by the energy partition between the EM and HAD compartments of the calorimeter. We note that the jet resolution has other contributions, for example, from underlying events and from gluon radiation. At first blush, the effects of the calorimetry itself are not dominating. In particular, SUSY searches are most compromised not by Gaussian terms in the resolution but by "tails". We do not observed tails induced by the CMS calorimetry at this level of modeling.

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References:

1. R. Wigmans, "Advances in Hadron Calorimetry", Ann. ReV. Nuc. Part. Sci., 41, (133), 1991

2. Pawel de Barbaro - private communication

3. CMS Technical Proposal, CERN/LHCC 94-38, Dec. 15, 1994

4. H. Abramowicz et al, Nuc. Inst. and Meth. 180 (429) 1981

5. S. B. Kim and S. Vejcik, CDF/ANAL/TOP/CDFR/3006 (1995)

Figure Captions:

Figure 1 The pie/e ratio for H4 test beam data with a weighting of ECAL for 15, 35, 50, 80, 120 and 375 GeV pions. The plot is In(Eo) vs pie/e for,

a. weighting of 1.4

b. weighting of 1, i.e. a muon calibration of ECAL and HCAL

Figure 2 The energy resolution (dE/E)^2 vs 1/E for H4 test beam data with a weighting of ECAL for 15, 35, 50, 80, 120 and 375 GeV pions.

a. weighting of 1.4

b. weighting of 1, or muon calibration

Figure 3 Response of the CMS calorimeter to jets using the unweighted, or muon calibration for jets with Pt = 50, 100, 200, 400, 800 and 1600 GeV.

a Ptrec/Ptgen vs ln(Ptgen)

b. (dPtrec/Ptrec)^2 vs l/Ptrec.

Figure 4 Transverse energy flow within a jet with Pt = 500 GeV. The plot is of Ptrec/Ptgen as a function of cone size R.

Figure 5 Histogram of Ptrec/Ptgen for 2000 jets with Pt = 500 GeV.

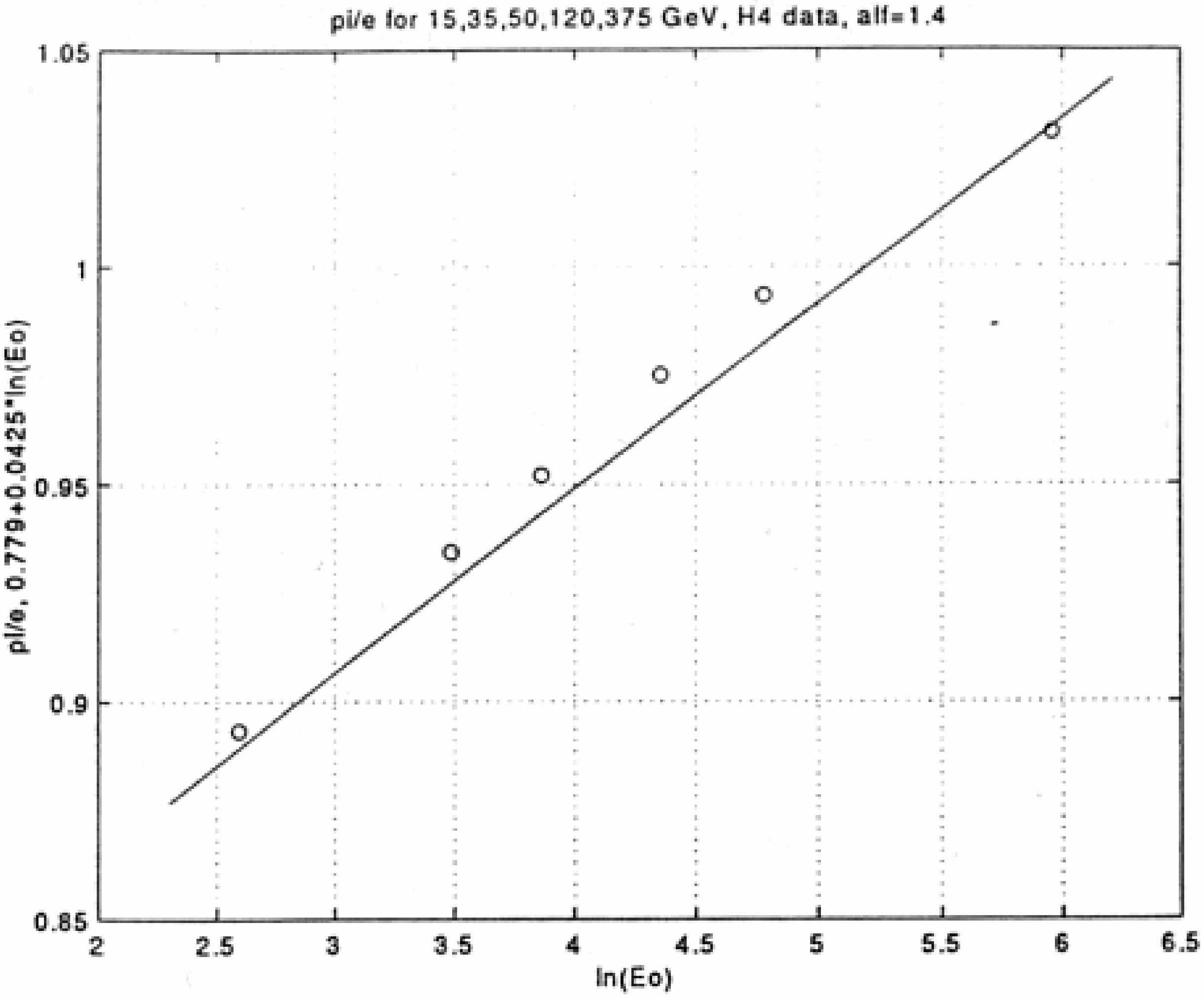
a. For hadrons with muon calibration.

b. For jets with a zo correction.

Figure 6 Scatterplot for 500 GeV Pt jets of zo vs Ptrec/Ptgen.

Figure 7 a. Scatterplot of neutral fraction, zo, of a Pt = 500 GeV jet vs the fraction of the jet energy in the EM compartment.

b. Scatterplot of the ratio Ptrec/Ptgen for 500 Gev jets vs the fraction of the jet energy in the EM compartment.


pi/e for 15,35,50,120,375 GeV, H4 data, alf=1.4
pi/e, 0.779+0.0425*ln(Eo)
ln(Eo)

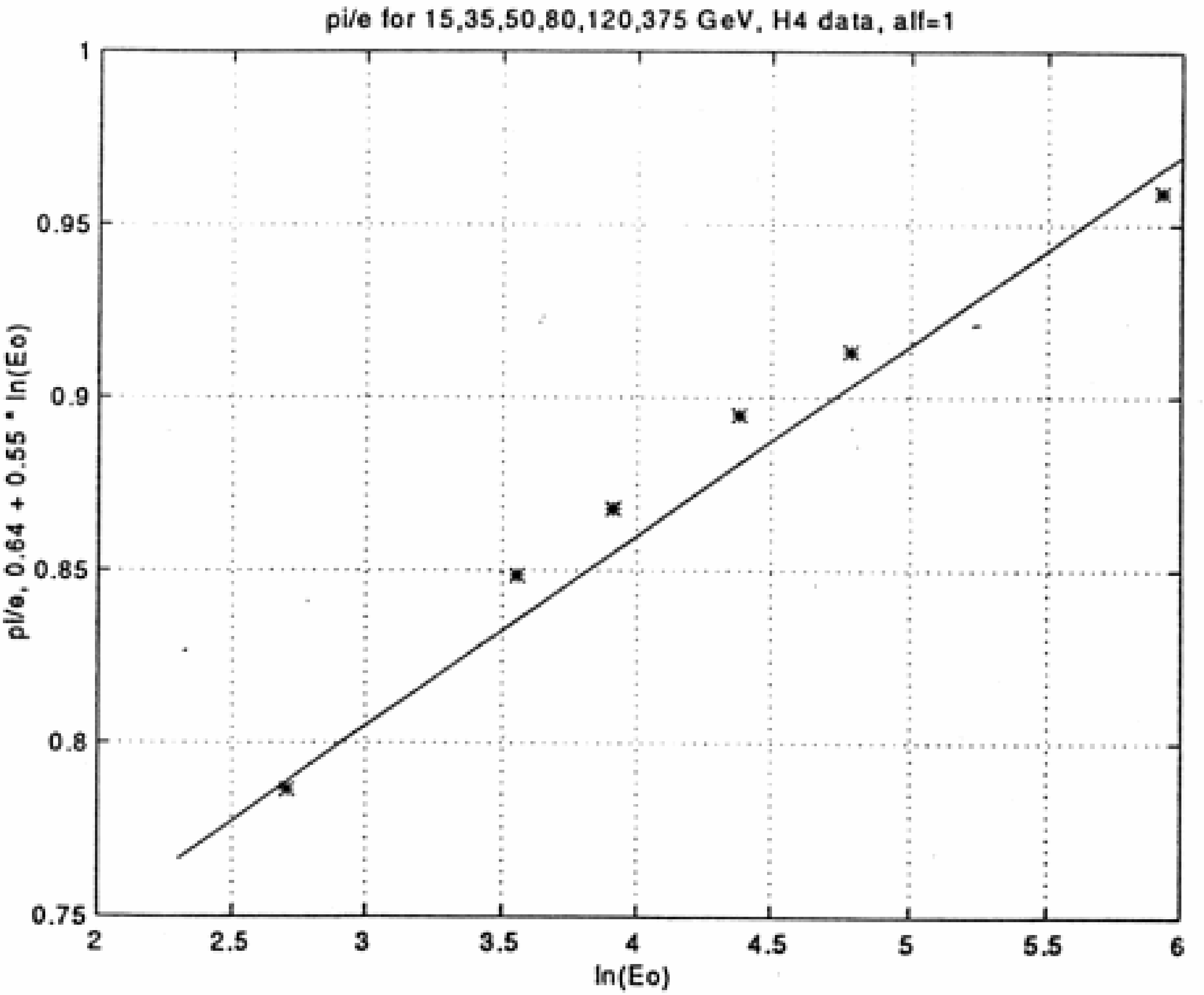
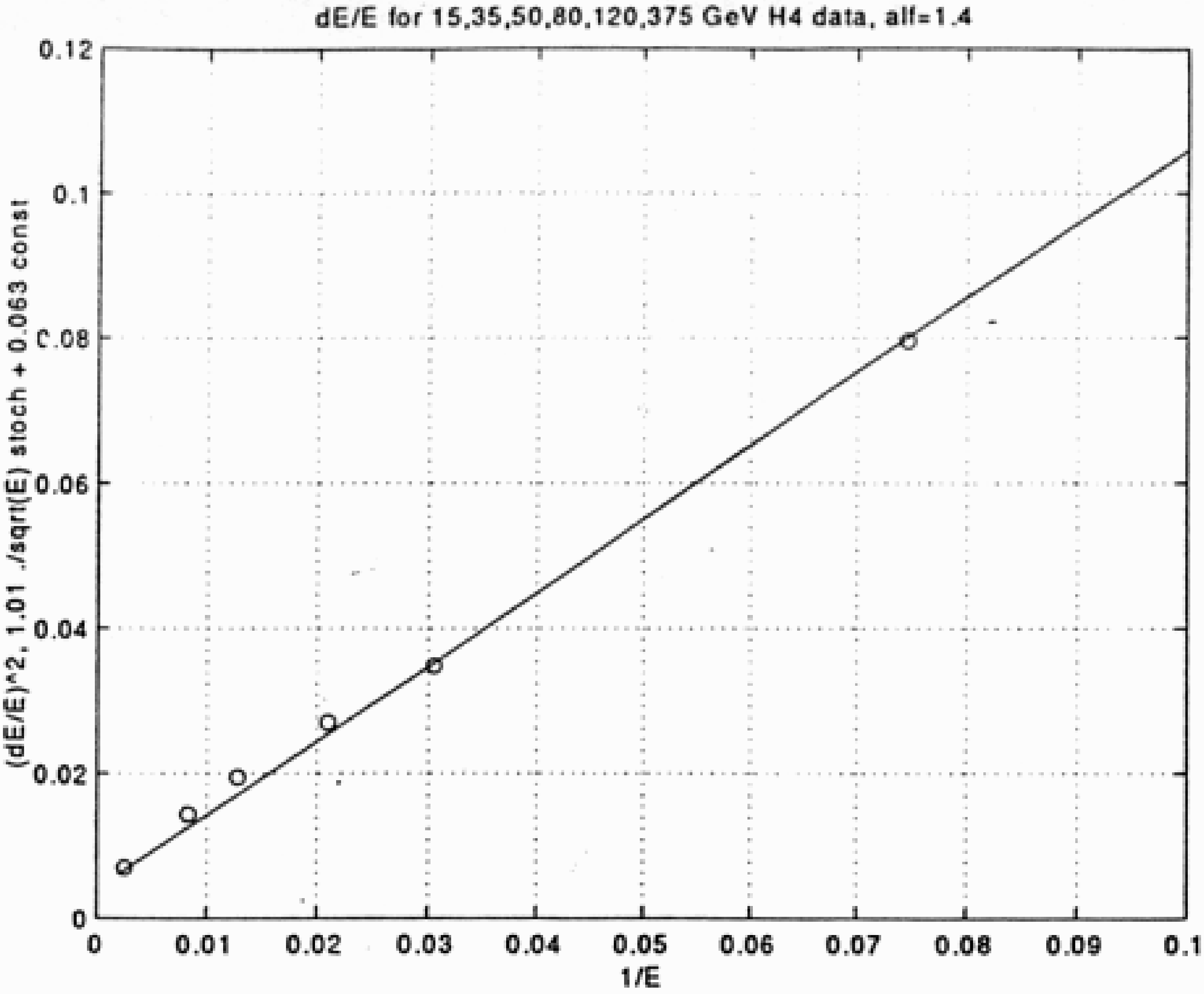

pi/e for 15,35,50,80,120,375 GeV, H4 data, alf=1
pi/e, 0.64 + 0.55 * ln(Eo)
ln(Eo)

Figure 1


dE/E for 15,35,50,80,120,375 GeV H4 data, alf=1.4
(dE/E)^2, 1.01 ./sqrt(E) stoch + 0.063 const
1/E

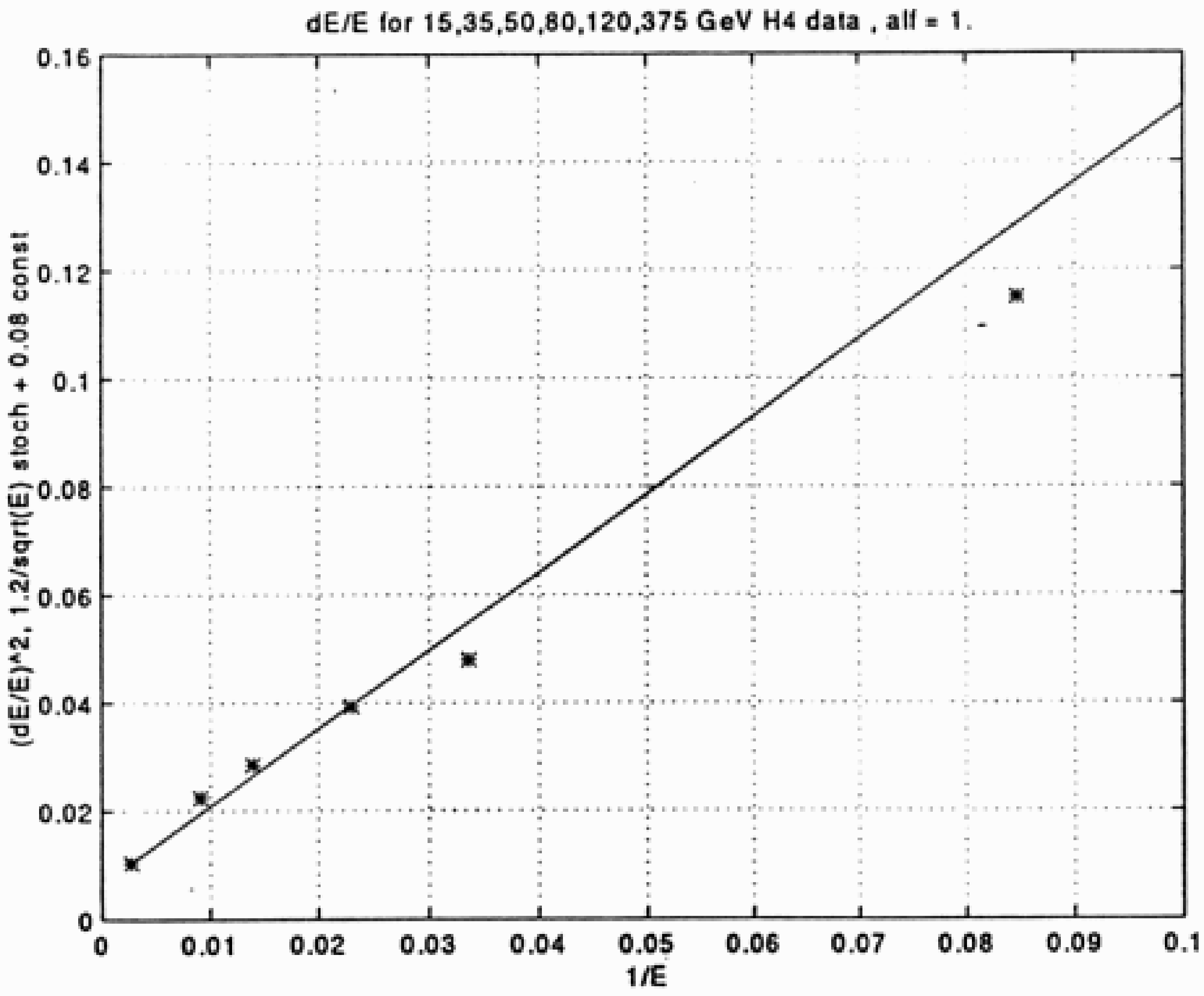
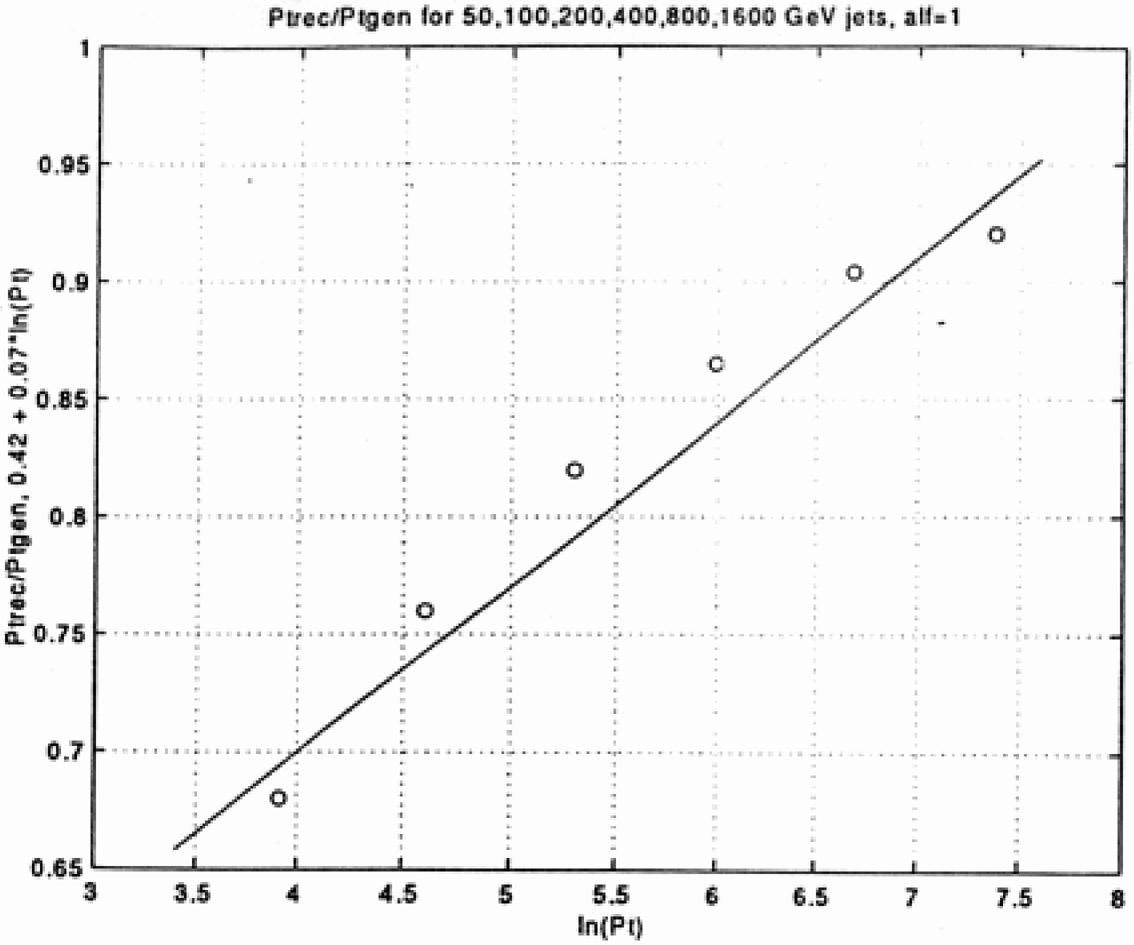
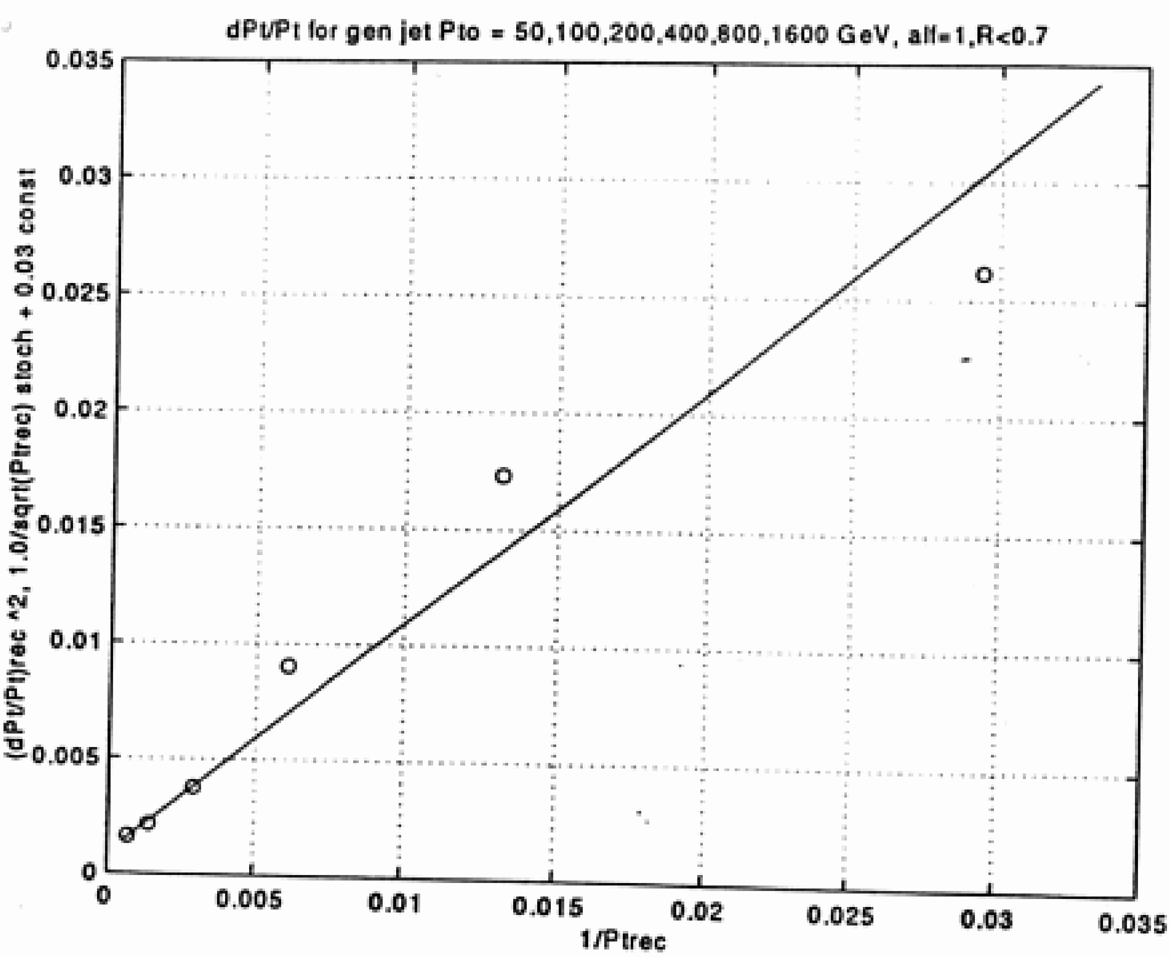

dE/E for 15,35,50,80,120,375 GeV H4 data , alf = 1.
(dE/E)^2, 1.2/sqrt(E) stoch + 0.08 const
1/E

FIGURE 2

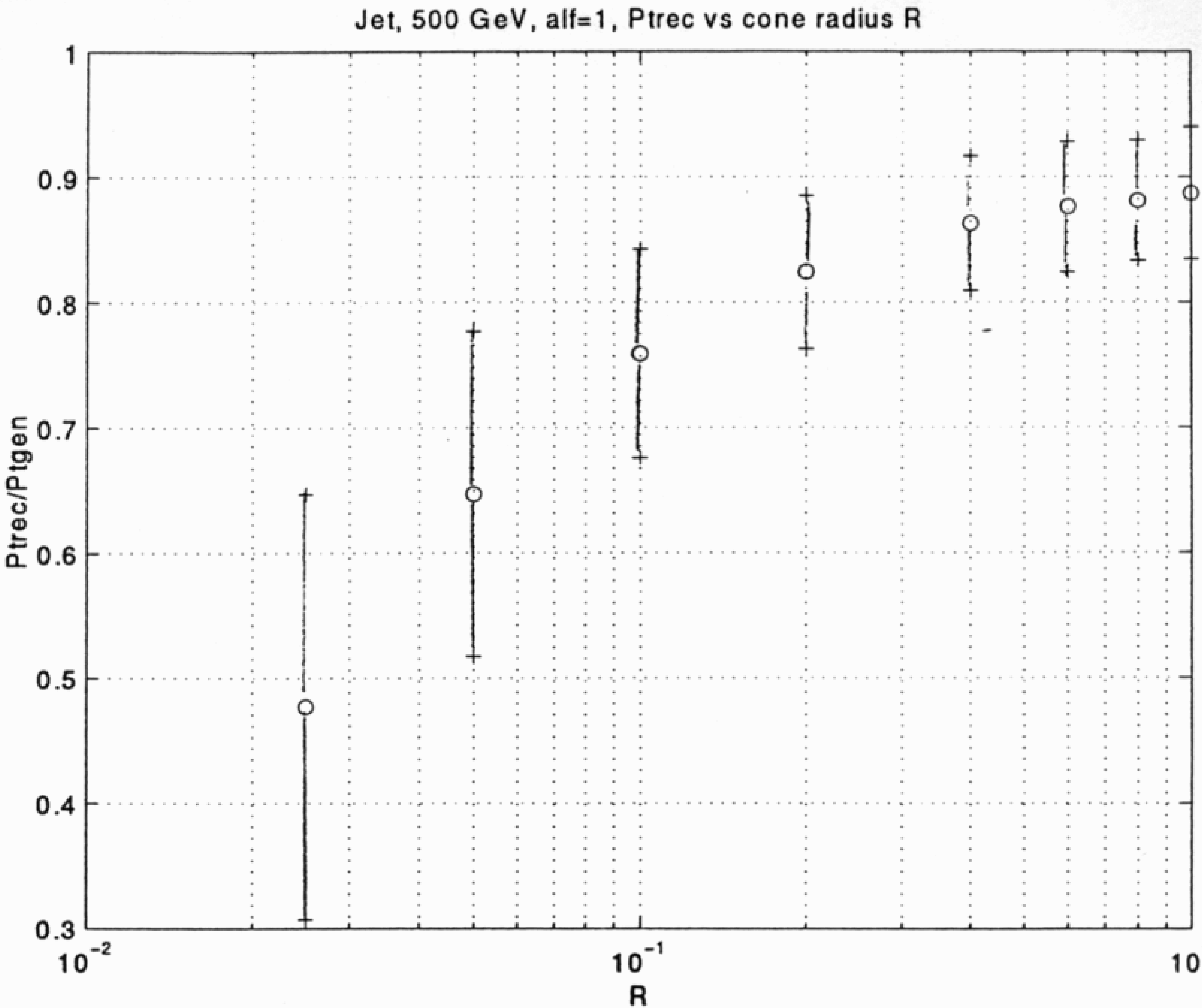


Ptrec/Ptgen for 50,100,200,400,800,1600 GeV jets, alf=1
Ptrec/Ptgen, 0.42 + 0.07*ln(Pt)
ln(Pt)
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8



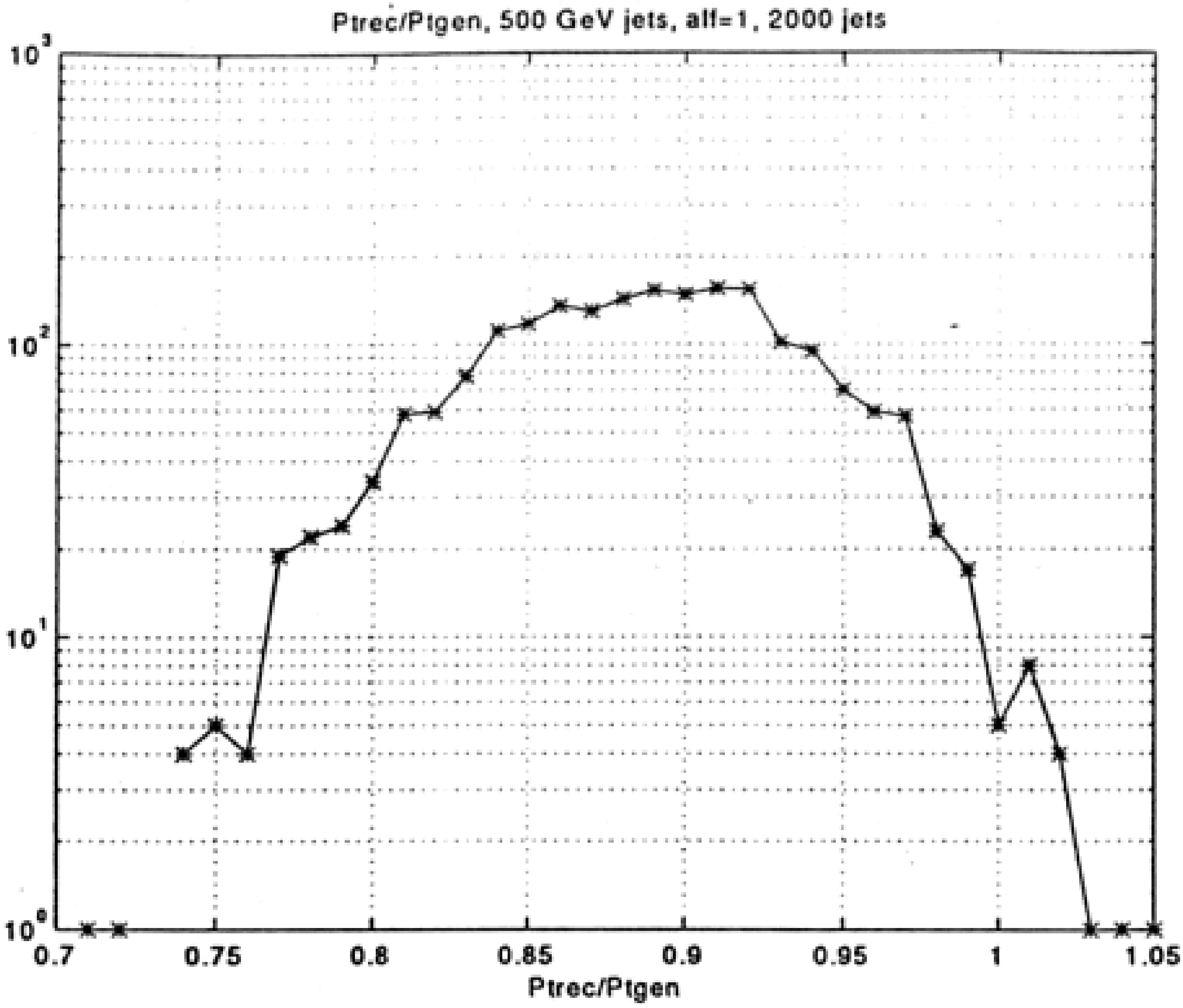
dPt/Pt for gen jet Pto = 50,100,200,400,800,1600 GeV, alf=1,R<0.7
(dPt/Pt)rec ^2, 1.0/sqrt(Ptrec) stoch + 0.03 const
1/Ptrec
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035

Figure 3



Jet, 500 GeV, alf=1, Ptrec vs cone radius R
Ptrec/Ptgen
R
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
10^{-2}
10^{-1}
10^{0}

Figure 4


Ptrec/Ptgen, 500 GeV jets, alf=1, 2000 jets
Ptrec/Ptgen

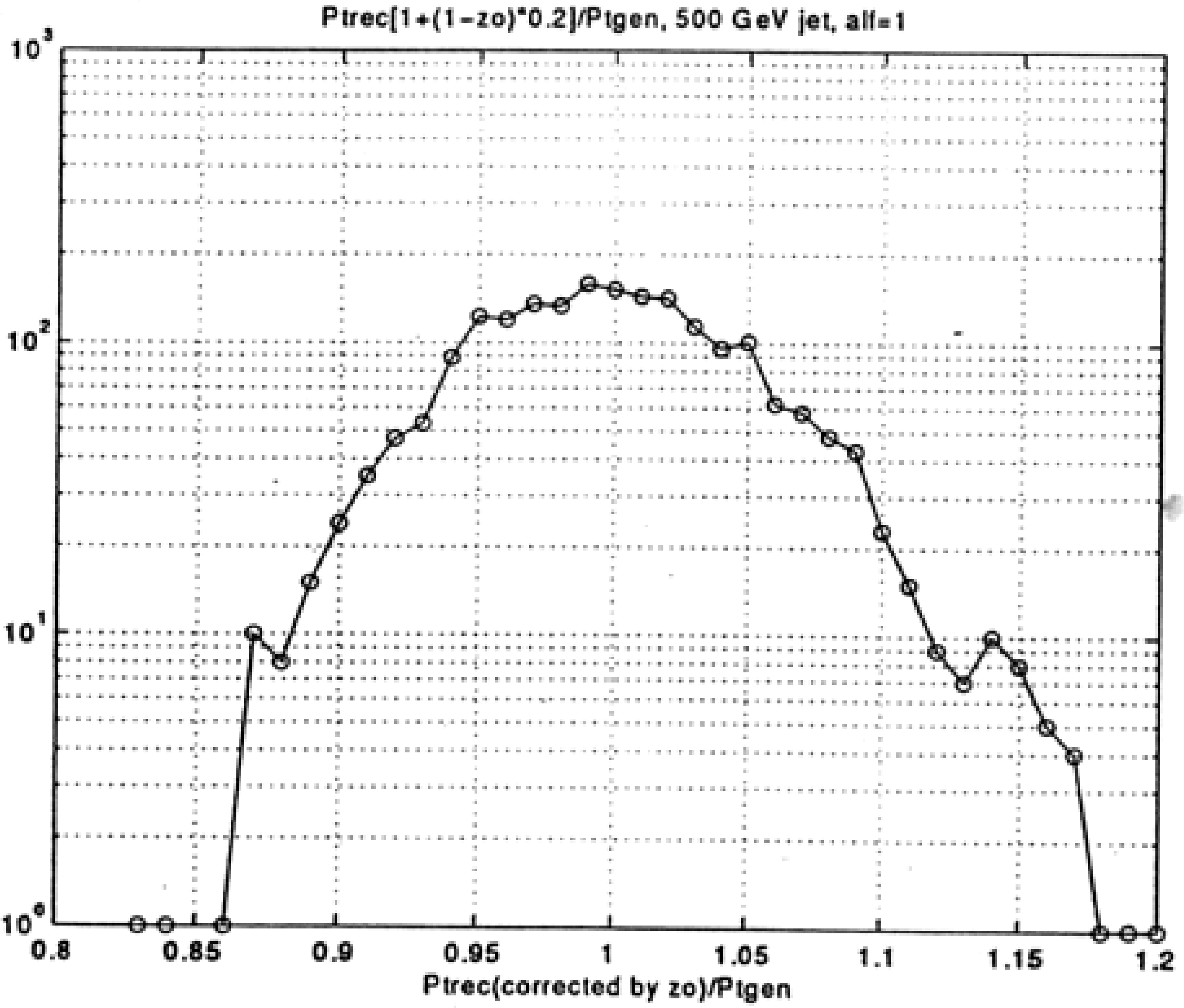

Ptrec[1+(1-zo)*0.2]/Ptgen, 500 GeV jet, alf=1
Ptrec(corrected by zo)/Ptgen

Figure 5

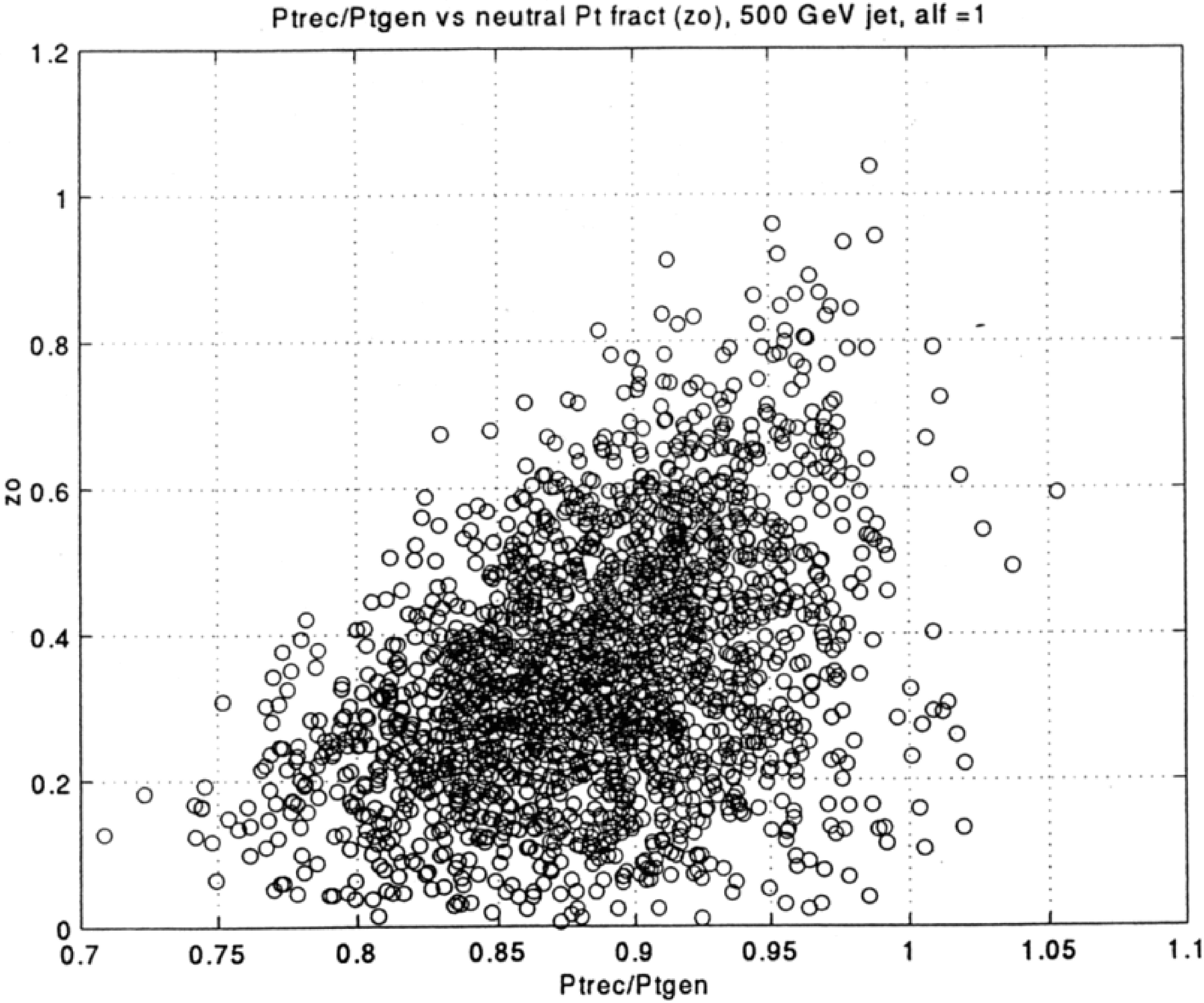

Ptrec/Ptgen vs neutral Pt fract (zo), 500 GeV jet, alf =1
zo
1.2
1
0.8
0.6
0.4
0.2
0
0.7
0.75
0.8
0.85
0.9
0.95
1
1.05
1.1
Ptrec/Ptgen

FIGURE 6

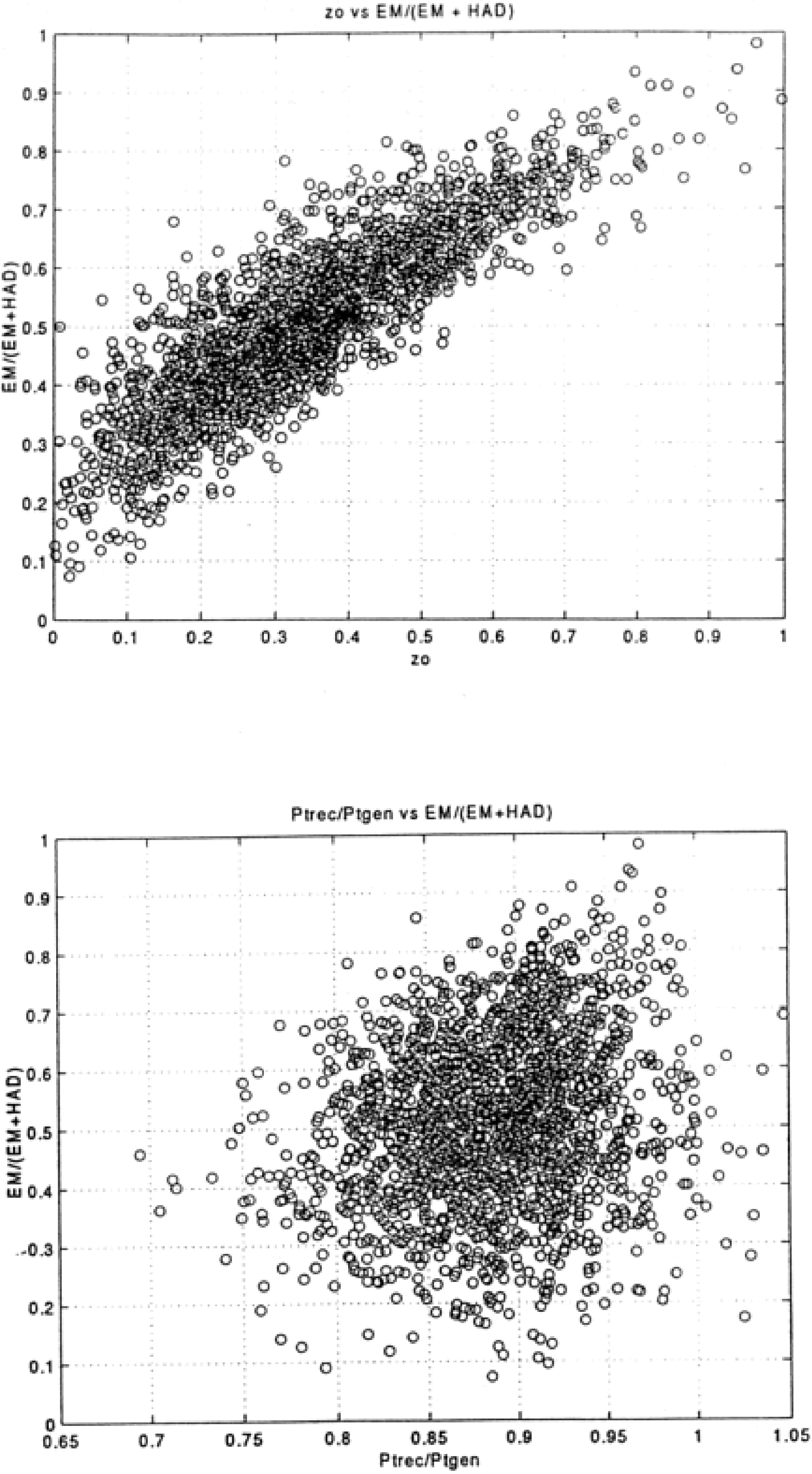

zo vs EM/(EM + HAD)
EM/(EM+HAD)
zo
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Ptrec/Ptgen vs EM/(EM+HAD)
EM/(EM+HAD)
Ptrec/Ptgen
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1.05

Figure 7